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Late Wisconsin glaciation of Hadwen and Summer islands, Tuktoyaktuk Coastlands, NWT, Canada

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ABSTRACT
The exact timing of the last major advance of the Laurentide Ice Sheet onto the Beaufort Sea coastlands of western Arctic Canada is unclear but significant to our understanding of landscape change and palaeo-ice stream chronology. Optical stimulated luminescence dating of preglacial and postglacial aeolian sand from Hadwen and Summer islands, in the Tuktoyaktuk Coastlands, indicates that glaciation took place between about 17.5 and 15 ka, and most likely between 16.6 and 15.9 ka, coinciding with Heinrich event 1. At this time the Mackenzie Trough palaeo-ice stream advanced into a cold-climate sandy desert, interrupting aeolian activity.

RÉSUMÉ
La date exacte de la dernière grande avancée de l'Inlandsis laurentidien dans la mer de Beaufort dans l'ouest de l'Arctique canadien n'est pas clair, mais elle est significative pour notre compréhension des changements de paysage et de la chronologie des paléo-flux de glace. La datation avec la luminescence stimulée optiquement (OSL) de dépôts préglaciaires et de sable éolien postglaciaire, provenant de Hadwen et de Summer Islands près des côtes de Tuktoyaktuk, montre que les glaciations ont eu lieu entre environ 17,5 et 15 ka, et probablement entre 16,6 et 15,9 ka, coïncidant ainsi avec l'évènement de Heinrich 1. À ce moment, le paléo-flux de glace de la fosse Mackenzie s'est avancé dans un désert de sable de climat froid, interrompant ainsi l'activité éolienne.

1 INTRODUCTION

During the Wisconsin cold stage, the Laurentide Ice Sheet (LIS) advanced onto the present-day Beaufort Sea coastlands and continental shelf of western Arctic Canada (Figure 1). In the Tuktoyaktuk Coastlands the last major LIS glaciation occurred during the Toker Point Stadial (Rampton 1988). Despite growing consensus that this stadial was Late Wisconsin in age, the exact timing is unclear. It has previously been assigned variously to >35 ka (Early Wisconsin; Rampton 1988), within the period of about 34–20 ^{14}C ka BP (Dallimore et al. 1997), between 14,000 and 13,000 ^{14}C years BP (about 17–15 ka cal BP; Mackay and Dallimore 1992), 21–12 ka (Bateman and Murton 2006) and 22–16 ka (Murton et al. 2007). Bateman and Murton (2006, figure 9) plotted optical stimulated luminescence (OSL) ages for sands interpreted as preglacial and postglacial in the Summer Island and northern Liverpool Bay areas (Figure 1), near the margins of the Mackenzie Trough and Anderson palaeo-ice streams, respectively (Margold et al. 2015). The aim of the present study is to refine this plot and date more precisely the advance of the Mackenzie Trough palaeo-ice stream onto Hadwen and Summer islands, where we now have the best available stratigraphic understanding and sequence of OSL ages for pre- and postglacial sediments. Here we report observations on the lithostratigraphy and sedimentology and evaluate new and previously published OSL ages.

2 STUDY AREA

The main study area is located on the north coast of Hadwen Island (Figure 1), where the lithostratigraphic relationships between the preglacial and glacial deposits are clear and well exposed. The Pleistocene lithostratigraphy comprises brown sand of the Kittigazuit Formation (Fm) beneath pebbly clay (diamicton) of the Toker Point Member (Mb) of the Tuktoyaktuk Fm, (Rampton 1988; Terrain Analysis & Mapping Services Limited 1993). A pebble-boulder lag and / or aeolian dune and sand-sheet deposits cap many sections along the coastal bluffs (Bateman and Murton 2006). A second site is at Crumbling Point, Summer Island, where massive ice interpreted as buried basal ice of the LIS is penetrated by postglacial sand wedges and underlain by a glacitectonite and Kittigazuit Fm sand (Murton et al. 2005, table 3).

3 METHODS

3.1 Logging

Stratigraphic sections were examined and logged sedimentologically in several localities along the coastal bluffs of northern Hadwen Island to refine these observations and interpret the origin of the sediments and sedimentary structures. Section 08-14, located at 69° 35' 57.5"N; 134° 09' 02.6" W, was selected for dating of the Toker Point Stadial on the basis of cross-cutting relationships between the preglacial Kittigazuit Fm, Toker Point Mb till and a postglacial aeolian sand wedge (Figure

2). A clast fabric analysis of the till was carried out using methods reported in Murton et al. (2004, 2005).

3.2 OSL Dating

Samples for OSL were collected from freshly exposed vertical sections in opaque PVC tubes and prepared in order to clean and extract quartz at the Sheffield Luminescence laboratory as per Bateman and Catt (1996). OSL for all samples was measured using a Risø reader with optical stimulation provided by blue/green LEDs and luminescence detection was through a Hoya U-340 filter. The single aliquot regeneration (SAR) procedure was used to determine the palaeodose (De) (Murray and Wintle 2000, 2003). Between 14 and 24 replicate De measurements per sample were carried out. Data from aliquots were rejected if an aliquot exhibited poor growth of OSL with laboratory dose or if recycling values fell beyond 10% of unity. Once these and outliers were excluded, if replicate De values for samples had a low overdispersion and were normally distributed they were deemed to have been fully reset prior to burial and final De values were derived using a weighted mean with associated standard errors. For samples with OD >25% and skewing of De replicates partial resetting was assumed and final De values were derived using the finite mixture model (Roberts et al. 2000). Dose rates were calculated from *in situ* gamma spectrometry measurements with palaeomoisture based on those measured at present and a calculated cosmic dose contribution as per Prescott and Hutton (1994). The final ages are in calender years before 2005 and 2008, when samples were collected.

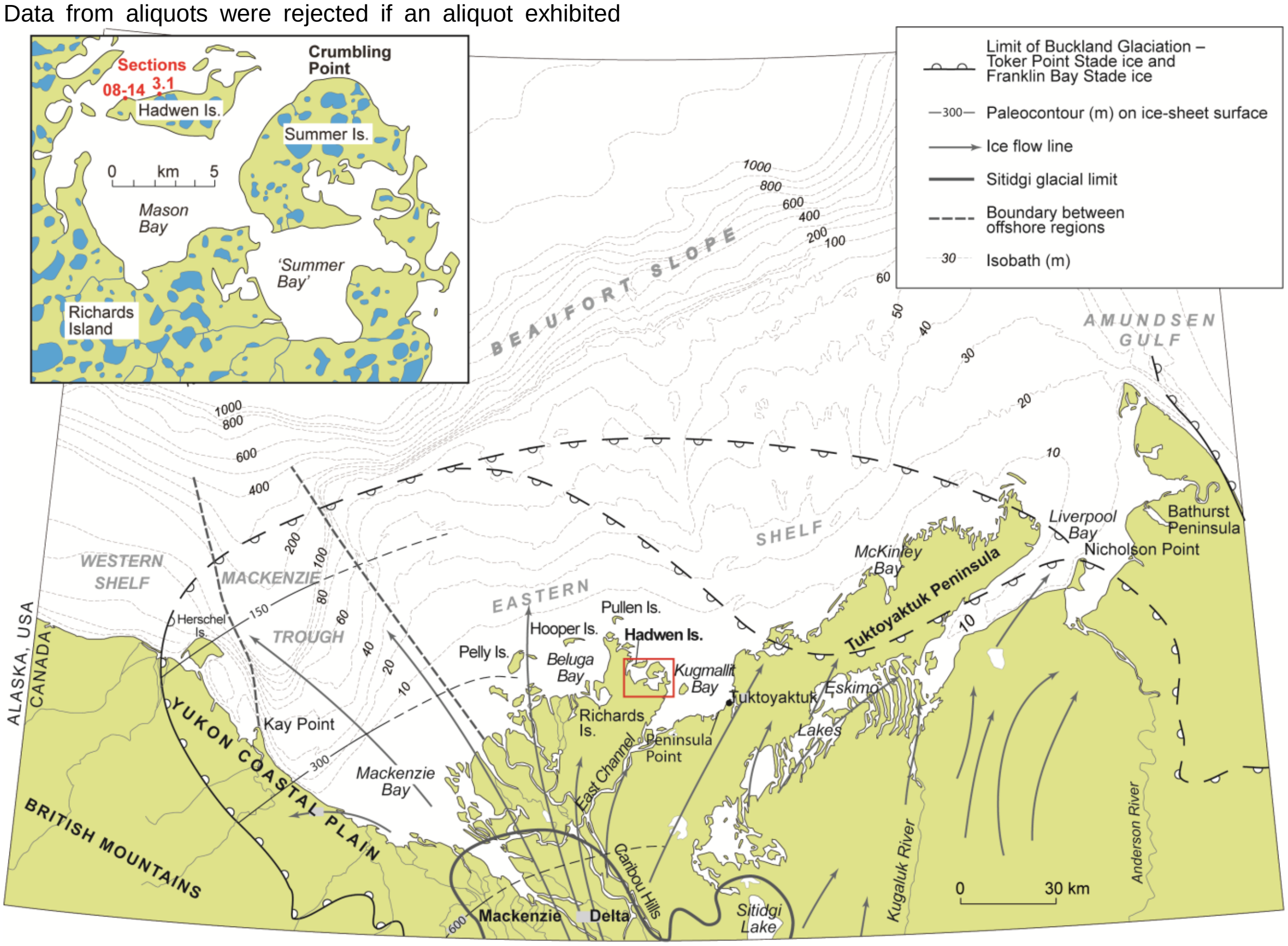

Figure 1. Location map of the Beaufort Sea coastlands and continental shelf. Ice flow lines and glacial limits after Rampton (1982, 1988): Buckland glaciation of the Yukon Coastal Plain, Toker Point Stadial glaciation of the Tuktoyaktuk Coastlands, and Franklin Bay Stadial glaciation of Amundsen Gulf. An alternative glacial limit for the Toker Point Stadial crosses the eastern Beaufort Sea Shelf north of the Tuktoyaktuk Pensinsula, indicating uncertainty about the topographic profile of the ice sheet here (Rampton, 1988). Inset map shows study area and field sites. Modified from Murton (2009).

4 RESULTS

4.1 Sedimentology and Stratigraphy

The Toker Point Mb diamicton in section 08-14 overlies the Kittigazuit Fm and is cross-cut by a sand wedge (Figure 2; Table 1). The diamicton is massive and matrix-supported. Its lower contact sharply overlies a layer of sand 0.15–0.2 m thick that is massive to faintly stratified, and contains lenses aligned more or less parallel to the layer. A clast fabric measured from the diamicton provided a value of fabric isotropy ($I = S_3/S_1$) of 0.050, a value of fabric elongation (E = 1 – (S_2/S_1)) of 0.931 and a mean lineation vector of 042°/272°. The high value of fabric elongation and low value of fabric isotropy indicate a strong preferred orientation of elongate clasts. The lower contact of the sand layer is sharp, truncating foresets in the underlying Kittigazuit Fm. Some foresets have oversteepened and folded tops, and some are displaced by horizontal shears directly beneath the sand layer. The diamicton is cross-cut by a sand wedge about 3 m high and 1 m wide (Figure 2).

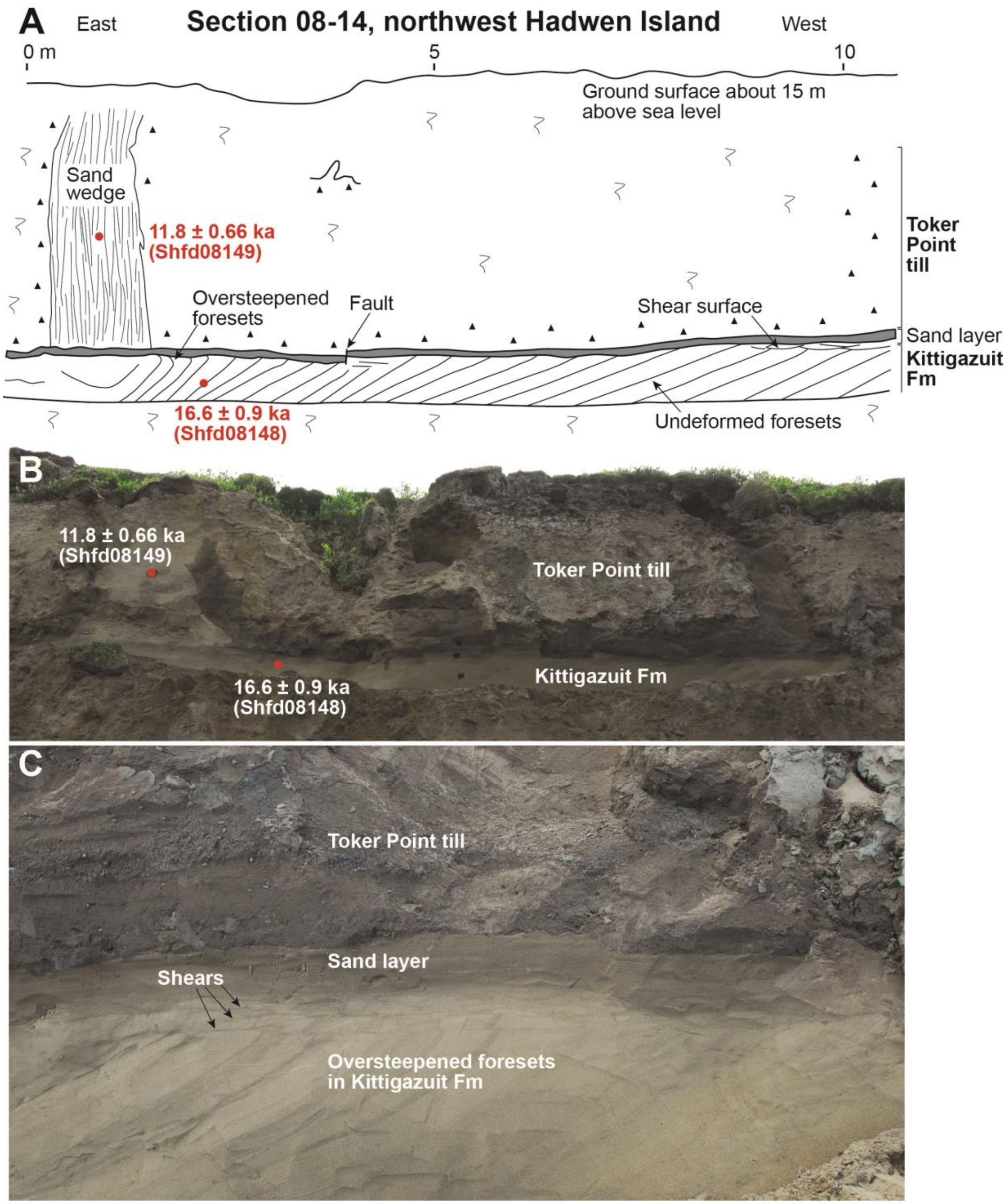

Figure 2. Kittigazuit Formation beneath Toker Point Till Member, section 08-14, northwest Hadwen Island. (A) Schematic sketch section showing stratigraphy and OSL ages. (B) Photograph of section. (C) Close-up photograph of oversteepened (towards left) and sheared foresets in Kittigazuit Fm beneath Toker Point Till.

Table 1. Lithostratigraphy and sedimentology of section 08-14, northwest Hadwen Island

Unit (thickness)	Description	Interpretation
Sand wedge	Fine sand, vertically to subvertically laminated, laminae 1 to several millimetres thick; wedge about 1 m wide, 3 m high; flat bottom of wedge at same depth as base of adjacent diamicton	Aeolian sand infilling thermal contraction cracks Postdates till because wedge cross-cuts till
Toker Point Mb (1–4 m)	5Y 3/1 (very dark grey, moist), massive, sandy to silty clay matrix, texturally variable; matrix-supported diamicton; pebbles and cobbles up to 8 cm in maximum dimension, rounded to subangular, dispersed (not abundant); lower contact sharp and undulating; diamicton crops out more or less continuously for few hundred metres along bluff; 2 subfacies: (A) Clayey facies: dark grey, few centimetres thick along base and forming lenses near base; (B) Sandy facies: grey, dominant facies; pebblier towards surface; Clast fabric measured nearby is shown in Figure 3	Toker Point till Ice flow towards the northeast
Sand layer (0.15–0.2 m)	Grey, massive to faintly stratified sand; faint horizontal to subhorizontal, gently undulating lenses; sharp lower contact	Glacitectonically sheared and mixed sediments
Kittigazuit Fm (≥ 7 m)	Brown, fine sand and grey silty sand; well stratified, strata few millimetres to few centimetres thick, foresets dip at 24° towards 070°; upper 0.1–0.4 m of some foresets are oversteepened or sheared, with shears horizontal to subhorizontal and parallel to the lower contact of overlying sand layer	Preglacial aeolian dune sand Glacitectonic overturning or shearing of the tops of some foresets

Table 2. OSL-related data for samples from section 08-14, northwest Hadwen Island

Stratigraphic unit	Lab. code	Depth from surface (m)	Palaeodose, De (Gy)	Dose Rate (Gy/ka)	Age (ka)
Sand wedge penetrating till	Shfd08149	2.4	19.41 ± 0.45	1.738 ± 0.090	11.8 ± 0.66
Kittigazuit Fm 0.4 m below till	Shfd08148	4.45	27.62 ± 0.66 [a]	1.652 ± 0.085	16.6 ± 0.9

[a] De based on finite mixture modelling.

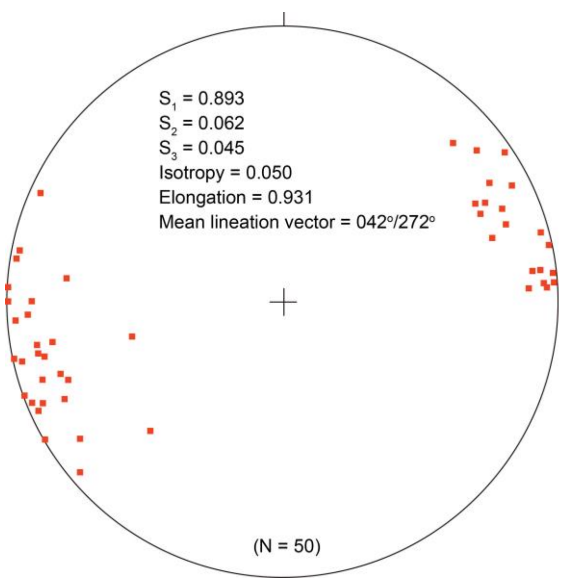

Figure 3. Schmidt equal-area stereonet of clast fabric from Toker Point till, near section 08-14, northwest Hadwen Island. The three principal eigenvalues are S_1, S_2 and S_3.

4.2 OSL Dating

The Kittigazuit Fm provided an OSL age of 16.6 ± 0.9 ka at a depth of 0.4 m below the Toker Point till in section 08-14 (Figure 2; Table 2). A sand wedge that cross-cut the till provided an OSL age of 11.8 ± 0.66 ka.

5 DISCUSSION

5.1 Glacial Processes

The strong preferred orientation of elongate clasts within the Toker Point till and their mean lineation vector of 042/272° are consistent ice flow towards the northeast. The ice movement glacitectonically deformed some of the uppermost Kittigazuit Fm sand. Deformation oversteepened and / or sheared foresets, and mixed sand and diamicton to form a sand layer at the contact of the diamicton and sand (Figure 2C). Collectively these features represent a glacitectonite (*sensu* Benn and Evans 1996). The horizontal bands of clayey facies and sandy facies in the basal part of the overlying diamicton suggest that this part of Toker Point 'till' also represents a glacitectonite that has been incompletely mixed.

5.2 Age of the Toker Point Stadial Glaciation

The age of the Toker Point Stadial glaciation on Hadwen Island is thought to be between about 17.5 and 15 ka based on OSL ages below till or below an erosion surface attributed to glaciation (Tables 2 and 3; Figure 4). Our best estimate for the maximum age of the glaciation is the OSL age of 16.57 ± 0.9 ka from Kittigazuit Fm sand beneath Toker Point till at section 08-14. In addition, OSL ages of 19.9 ± 1.1 ka and 25.6 ± 1.3 ka were obtained by Bateman and Murton (2006, figure 2) from Kittigazuit Fm sand beneath a prominent erosion surface that we attribute to glacial or glaciofluvial erosion during the Toker Point Stadial; this erosion surface is located at section 3.1, about 1.5 km east of section 08-14 (Figure 1 inset map). The minimum age for the glaciation is based on an OSL age of 16.12 ± 0.91 ka (Shfd02044) from Kittigazuit Fm sand 0.15 m above this erosion surface at section 3.1d. Additionally, a fading-corrected optical age of 16.1 ± 0.2 ka (SFU-0-160) on 180–250 μm potassium feldspar grains from a postglacial sand wedge at Crumbling Point, Summer Island (reported in Murton et al. 2007), provides a similar minimum age for onset of deglaciation (Table 3). ^{14}C ages of 12,500±110 years BP (GSC–3302) and 12,900±170 years BP (GSC–1321) on organic material from the basal part of lacustrine sediments on the Tuktoyaktuk Peninsula indicate that ice-free conditions commenced by about 15,500–14,300 cal years BP (Ritchie 1984). An age between 17.5 and 15 ka for the Toker Point Stadial glaciation supports Mackay and Dallimore's (1992) suggestion that ice advanced to the Tuktoyaktuk area between about 17 and 15 cal. ka.

Table 3. Previously published OSL ages on preglacial and postglacial aeolian sand on Hadwen and Summer islands

Stratigraphic unit	**Lab. code**	**Age (ka)**	**Significance**
Sand wedge in basal ice of LIS, Crumbling Point, Summer Island	SFU-0-160 [a]	16.1 ± 0.2	Postglacial aeolian sand
Kittigazuit Fm above major erosion surface, section 3.1, Hadwen Is.	Shfd 02046 [b]	15.57 ± 0.91	
	Shfd 02044 [b]	16.12 ± 0.91	
Kittigaz. Fm below major eros. surf., sect. 3.1, Hadwen Is.	Shfd 02045 [b]	19.9 ± 1.1	Preglacial aeolian sand
	Shfd 02043 [b]	25.6 ± 1.3	

[a] D.J. Huntley in Murton et al. (2007)
[b] Bateman and Murton (2006)

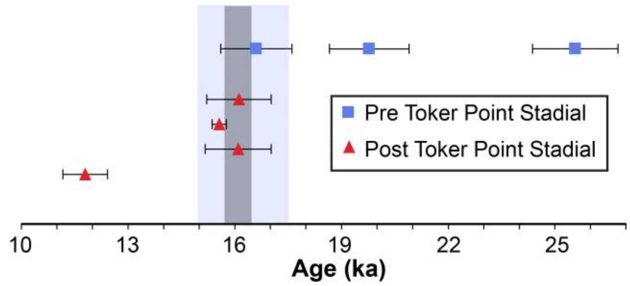

Figure 4. OSL ages on aeolian sand deposited before and after the Toker Point Stadial on Hadwen and Summer islands. Mean age of the three oldest postglacial ages is 15.93 ± 0.31 ka with uncertainty excluding original age uncertainty (indicated by dark grey bar) or 15.93 ± 0.96 ka including original uncertainty (light grey bar).

Glaciation of Hadwen Island is attributed to advance of the Mackenzie Trough palaeo-ice stream. Brief glaciation between 17.5 and 15 ka accounts for the permafrost thickness of about 700 m reported by Pelletier (1987) in the study area. Heat-flow calculations suggest that the time required to grow 500–600 m of permafrost probably exceeds 50,000 years (Mackay 1979), consistent with Hadwen and Summer islands having been ice-free and subaerially exposed for most of the Wisconsin (Taylor et al. 1996a, 1996b).

6 CONCLUSIONS

Glaciation of Hadwen Island during the Toker Point Stadial occurred sometime between about 17.5 and 15 ka (incorporating errors), most likely between 16.6 and 15.9 ka (Figure 4). This glacial advance coincided with Heinrich event 1. For most of the LGM, the study area was ice-free, allowing thick permafrost to form. The Mackenzie Trough palaeo-ice stream advanced into a cold-climate desert characterized by dunes and sand sheets of the Kittigazuit Fm, located in the distant rainshadow of mountains and the Cordilleran Ice Sheet to the southwest. Aeolian sedimentation resumed in some till-free areas after the advance and persisted until it was abruptly ended at about 12.9 ka by erosion attributed to an outburst flood (Murton et al. 2010).

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